Accelerator Operations Summary

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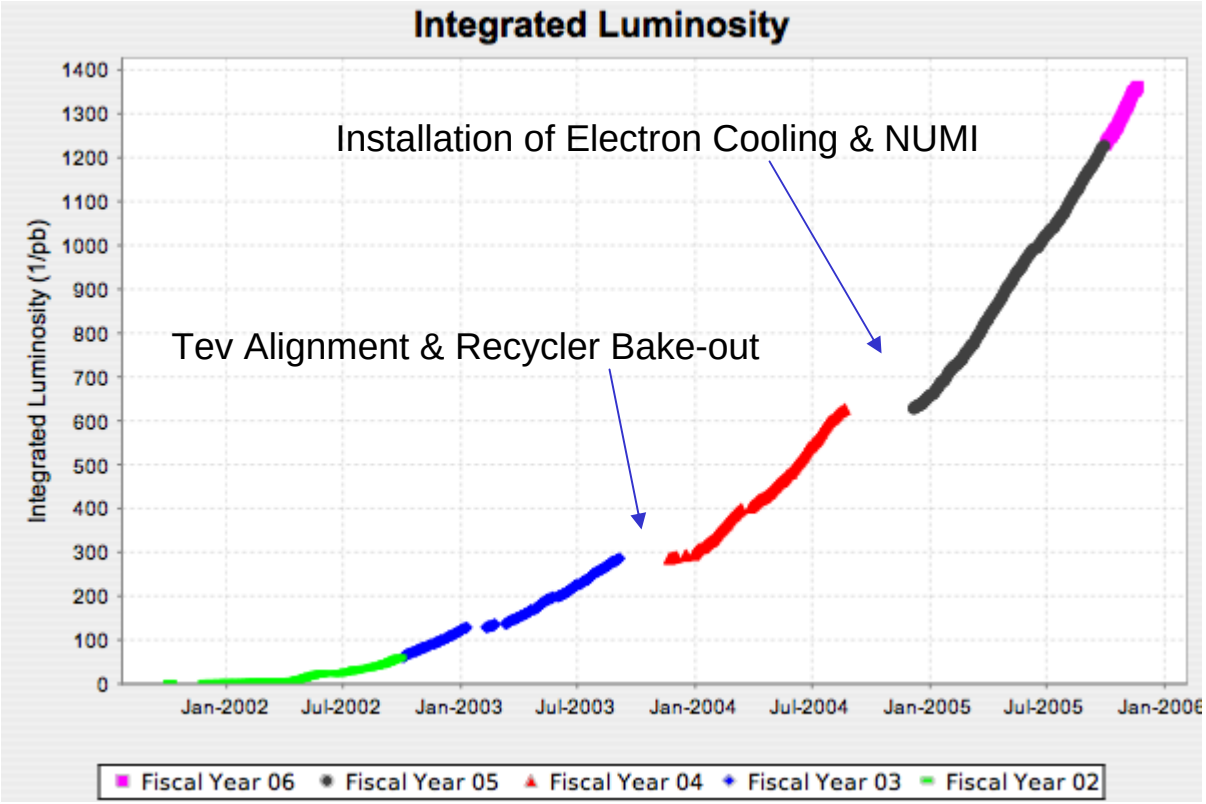
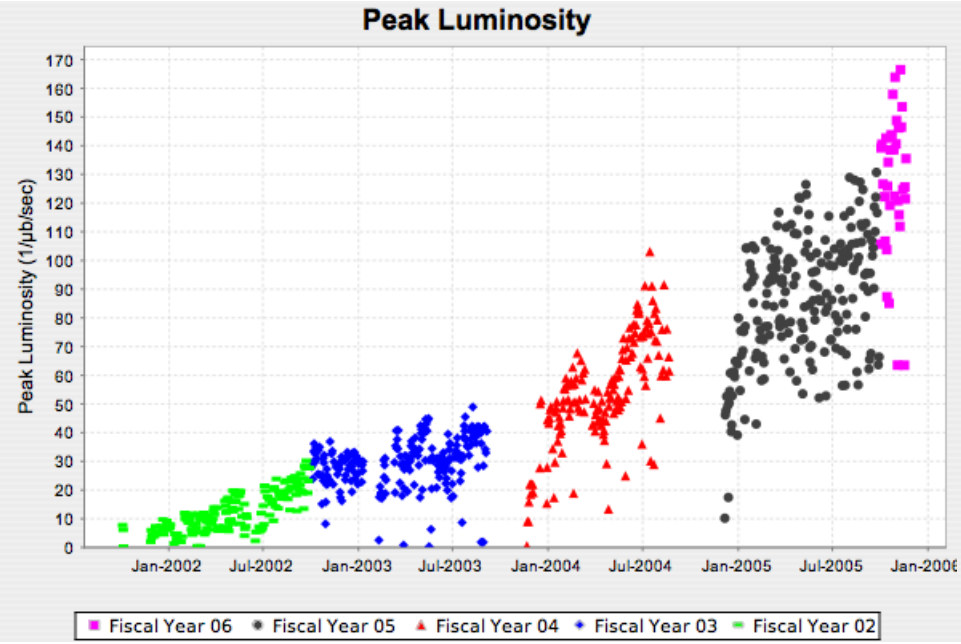
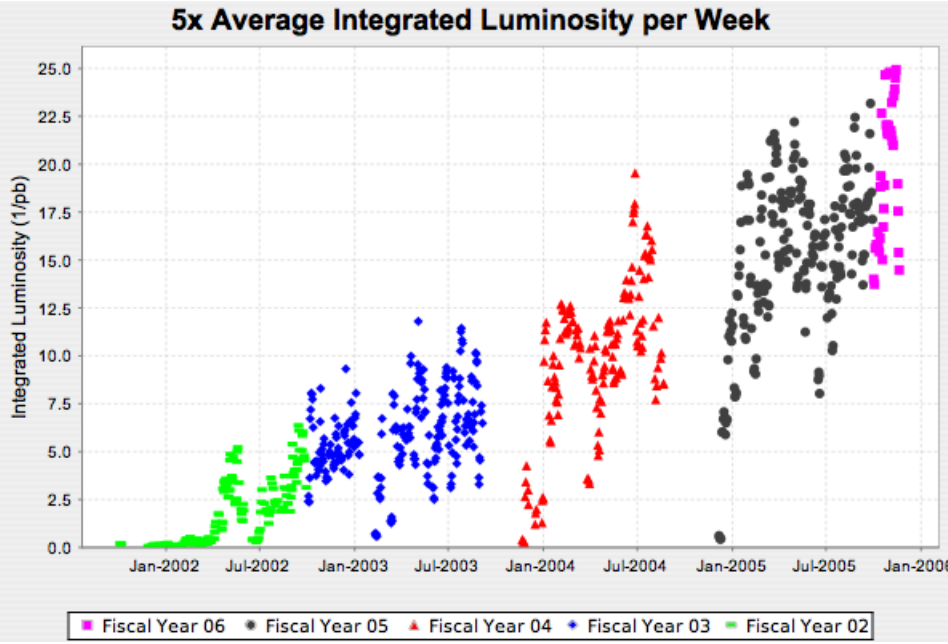
Integrated Luminosity



- Since June 2003, the Tevatron has seen a 3-fold increase in
  - Peak luminosity
  - Integrated luminosity per week
  - Total integrated luminosity

Luminosity History





- Luminosity increase is mostly due to:
  - Better performance of the injector chain
  - Introduction of the Recycler into operations
  - Alignment of the Tevatron
  - Decision to "run" the Collider
    - Rigorous approach to attacking operational problems
    - Focused study philosophy

Luminosity

$$L = \frac{3\gamma f_o}{\beta^*} B N_{\bar{p}} \frac{N_p}{\varepsilon_p} \frac{F\left(\beta^*, \theta_{x,y}, \sigma^L_{p,\bar{p}}, \varepsilon_{p,\bar{p}}\right)}{\left(1 + \varepsilon_{\bar{p}} / \varepsilon_p\right)}$$

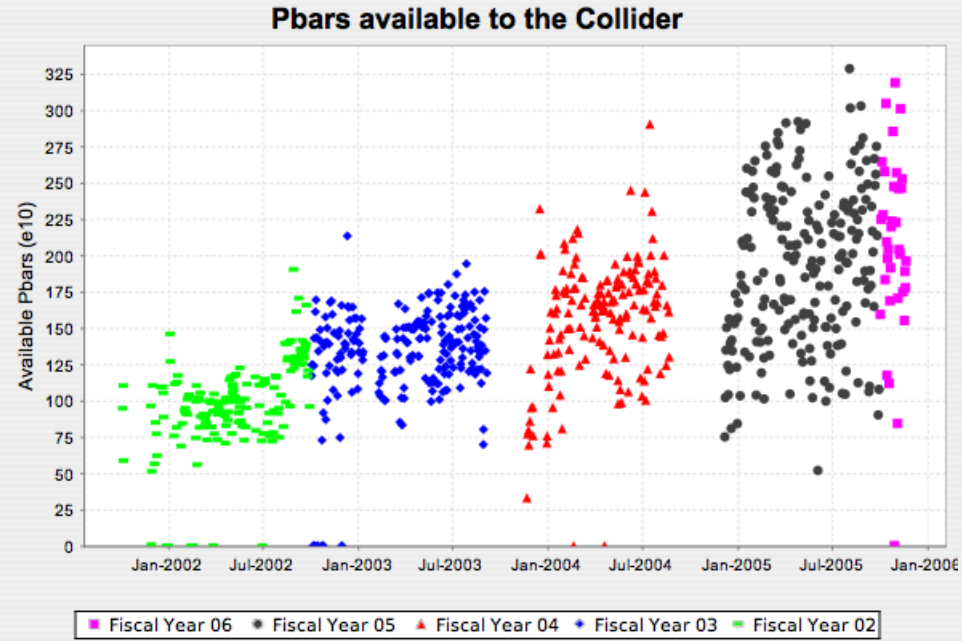
- The major luminosity limitations are
  - The number of antiprotons (BN_{pbar})
  - The proton beam brightness (N_p/ε_p)
    - Beam-Beam effects
  - Antiproton emittance
  - F<1

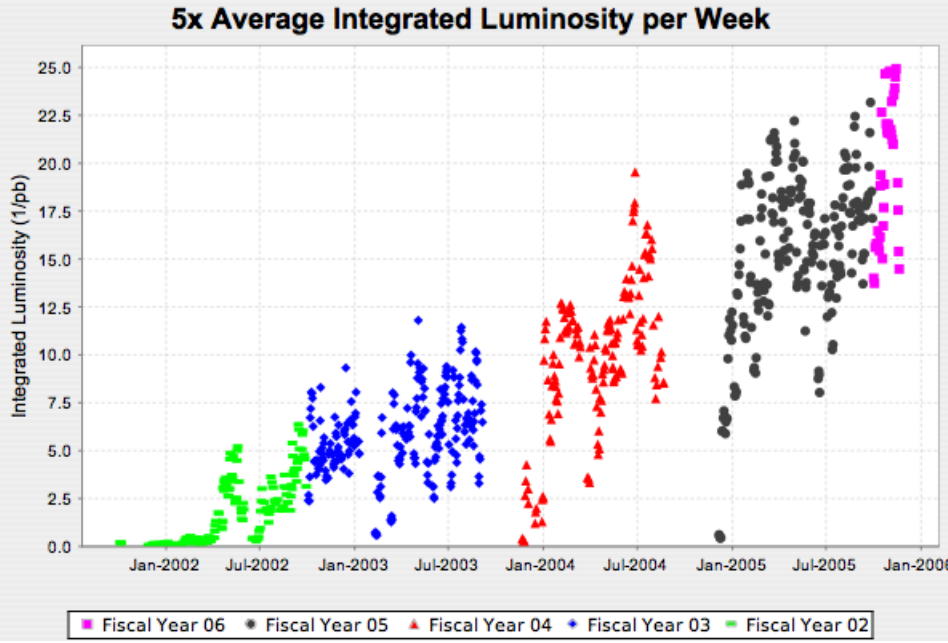
Antiproton Economics

$$\Phi_{\bar{p}}^{(\min)} = n_c \sigma_a L$$

- $n_c = 2$
- $\sigma_a = 70$ mb
- $L = 3.0 \times 10^{32}$ cm^{-2}-sec^{-1}
- $\Phi = 15 \times 10^{10}$ hr^{-1}

Antiprotons and Luminosity





- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Stacking Rate

$$\Phi = \frac{N_p P}{T_{rep}}$$

- N_p is the number of protons on target
- P is the production ratio of the number of antiprotons produced to N_p
  - Typically about 15-20x10^{-6}
  - Mostly a function of the collection aperture
- T_{rep} is the cycle time
  - Mostly a function of the cooling rate

Run II Upgrades

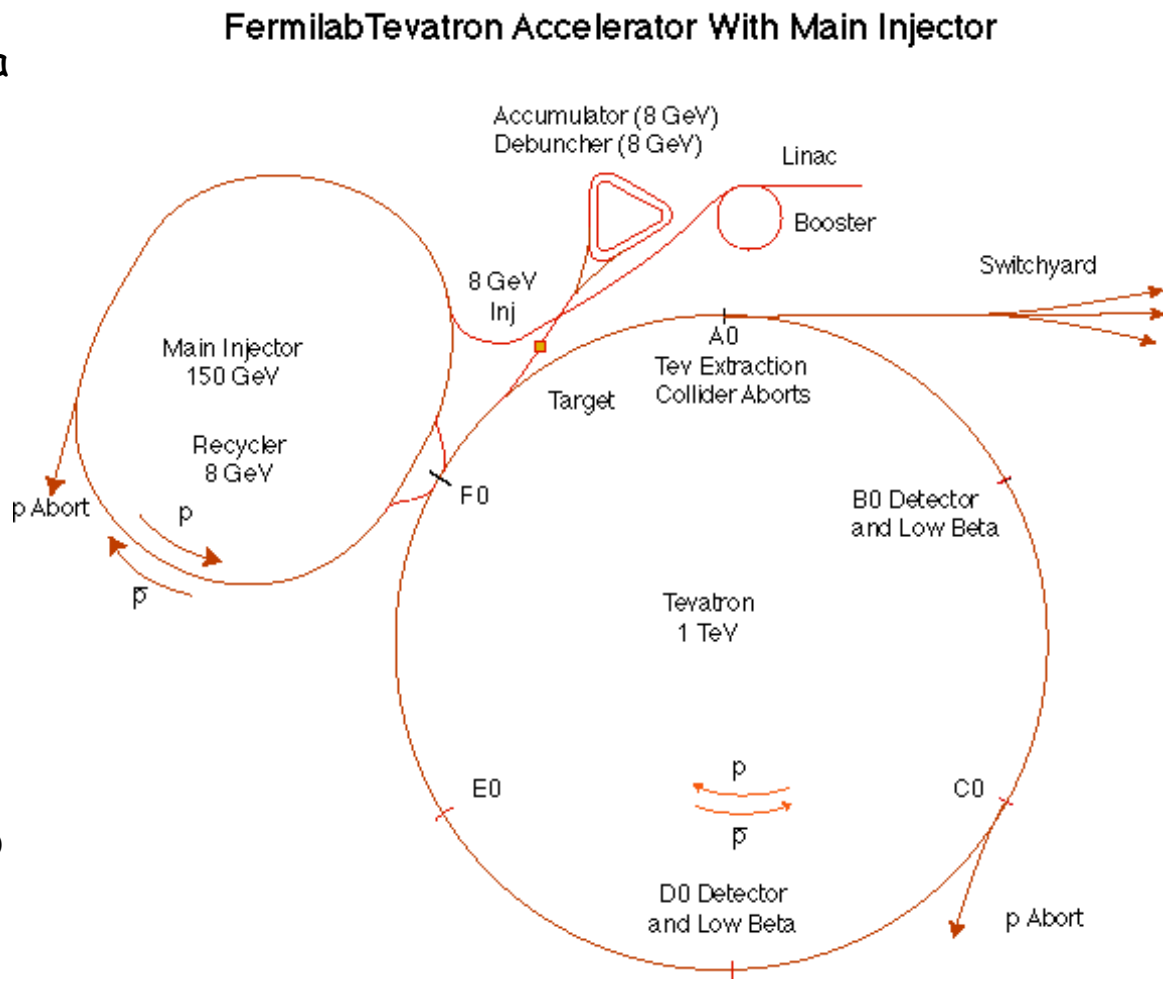
- More protons on the antiproton target
  - Slip stacking
    - MI Beam loading compensation
    - Booster Cogging
  - Intensity Goals:
    - Base: 6.5×10^{12}
    - Design: 8.0×10^{12}
- Better antiproton collection efficiency
  - Lithium lens gradient upgrade
  - AP2-Debuncher aperture increases
    - Physical aperture increases
    - Beam based alignment
  - Production Goals at a 2 second cycle time:
    - Base: 15×10^{-6}
    - Design: 21×10^{-6}
- Better cooling
  - Accumulator Stacktail
  - Electron cooling in the Recycler
  - Average Stacking Rate Goals:
    - Base: 9.7×10^{10}/hour
    - Design: 21.7×10^{10}/hour
- Rapid Antiproton Transfers
  - Transfer Time Goals
    - Base: 45 minutes
    - Design: 15 minutes

Stacking Progress

- The cornerstone of the Run II upgrades is antiproton production.
- The Phase 3 goal for the zero-stack stack rate is 20×10^{10} pbars/hour.
- Our best value to date is 17×10^{10} pbars/hour
- We have formed a special team of 20 people, dedicated 100%, to focus on antiproton production
  - Booster Extraction
  - Main Injector Slip Stacking
  - Antiproton Source
  - Instrumentation
- The goal of the stacking team is to:
  - Document the current state of the complex for antiproton stacking.
  - Formulate a study plan and needed instrumentation to reach 20×10^{10} pbars/hour
  - Successfully execute the plan by March 2006.
- The team meets twice a week at Tuesdays and Thursdays at 9 am in the Huddle to discuss overall progress and integration with collider operations.

Antiproton Production

- $1x10^8$ 8 GeV pbars are collected every 2-4 seconds by striking $7x10^{12}$ 120 GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- Each batch of Pbars are bunch rotated and pre-cooled in the Debuncher
- Multiple pbar batches (~8000) are momentum stacked and cooled in the Accumulator
- Every 4-6 hours the Accumulator stack is transferred to the Recycler where the new Accumulator batch is merged with the existing Recycler Stash and cooled with electron cooling
- After 24 hours of stacking, the 8 GeV Pbars are unstacked in the Recycler, transferred to the Main Injector and accelerated to 150 GeV and to 980 GeV in the TEVATRON

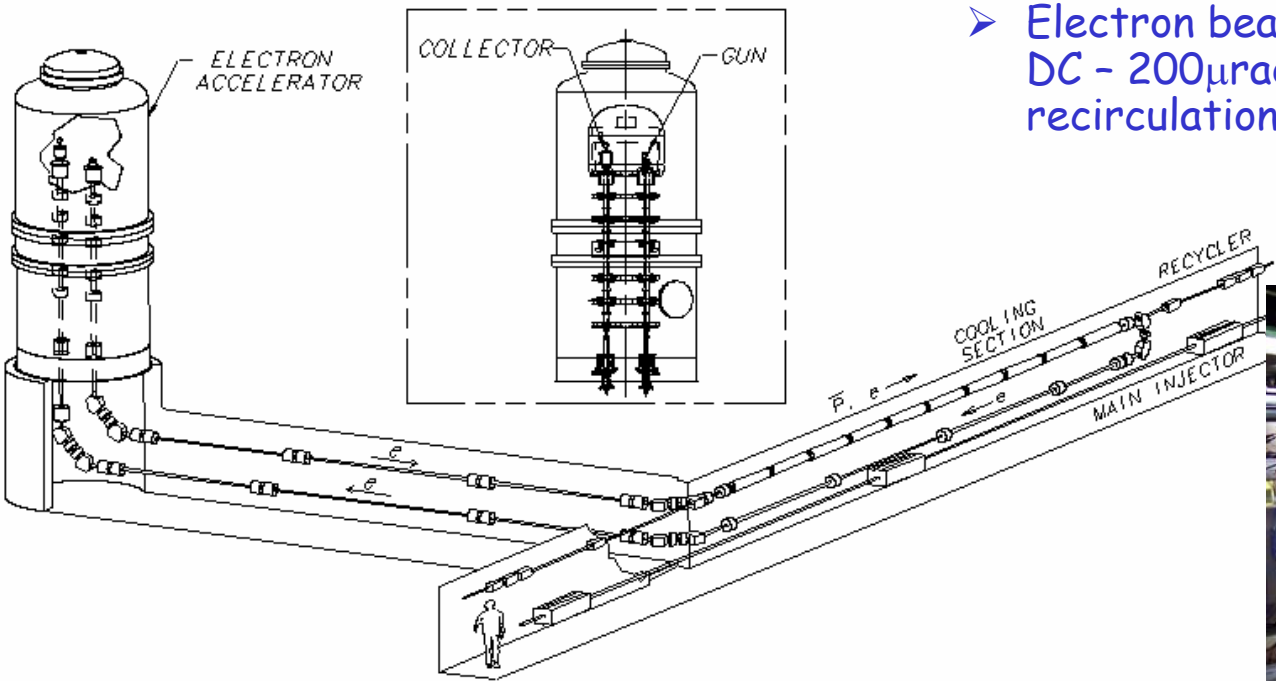


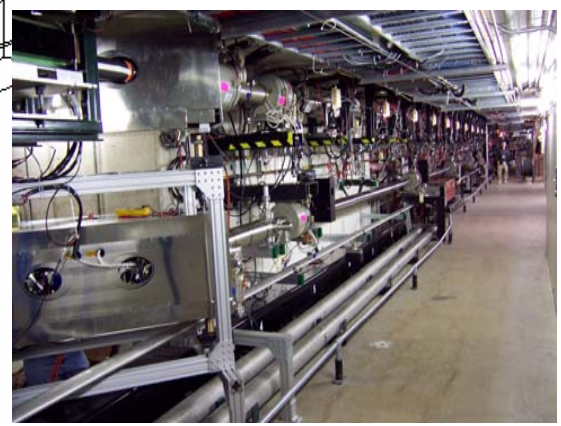
Recycler

- Features
  - Designed to a be a third stage antiproton accumulator ring
    - Initially uses stochastic cooling
    - Now starting to use electron cooling
  - Shares the same tunnel as the Main Injector
  - Major magnetic elements are made from permanent magnets
- At the end of August 2003
  - The Recycler was "on the ropes"
    - Lifetime was < 60hrs
    - Transverse emittance growth was 12π-mm-mrad/hr
  - Took drastic measures
    - Lengthened the Fall 03 shutdown to bake the entire Recycler
    - Instituted the Pbar Tax (Investment) to guarantee the Recycler adequate study time and access to the tunnel
    - Re-organized the Accelerator Physics Dept. to give the Recycler and Tevatron more accelerator physicists
- Recycler bake-out was extremely successful
  - Transverse emittance growth reduced by a factor of 10-20
  - Lifetime > 600 hours
- Recycler commissioning has progressed rapidly
  - Using the Recycler in "Combined Shots" operations makes it a luminosity enhancement
    - Operational January 2005
  - Transverse Damper commissioned August 2005
    - Stacks larger than $150x^{10}$ pbars now possible
  - Stand alone Recycler shots to the Tevatron (Sept 2005)
    - Stack of $190x10^{10}$ pbars in the Recycler
    - $92x10^{30}cm^{-2}sec^{-1}$ Luminosity
- Electron Cooling commissioned July 2005
  - By the end of August 2005, electron cooling is used on every Tevatron shot

Recycler Electron Cooling

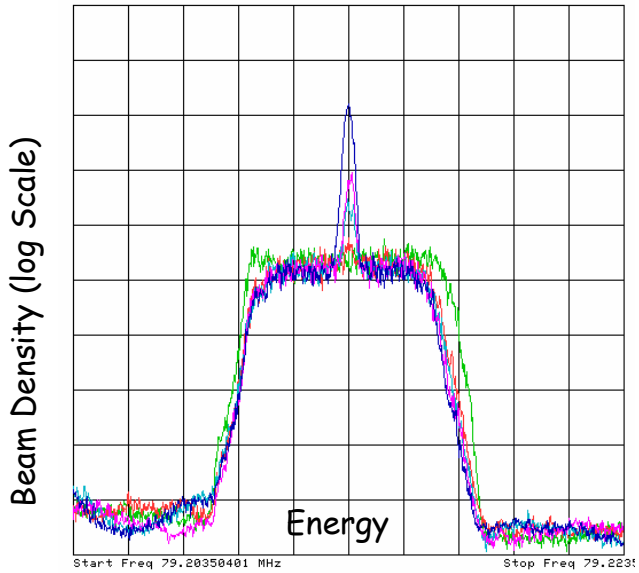
- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad beam spread – 99% recirculation efficiency

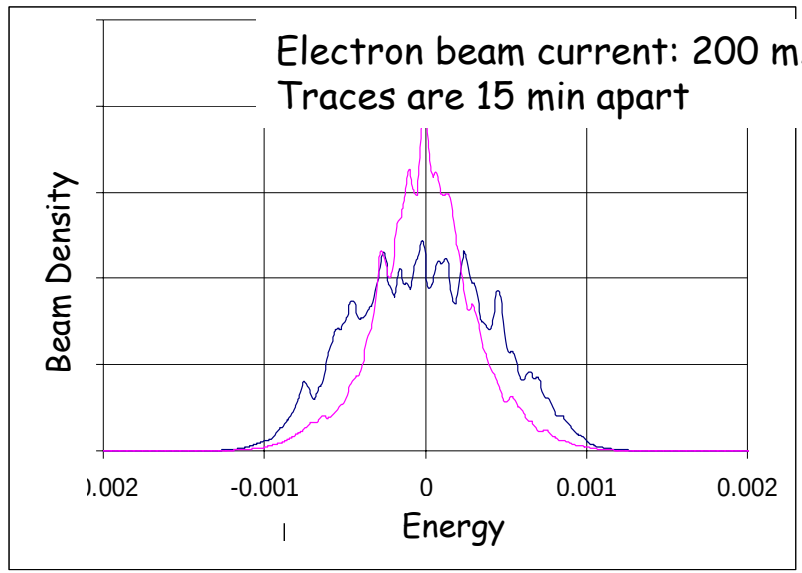




Recycler Electron Cooling

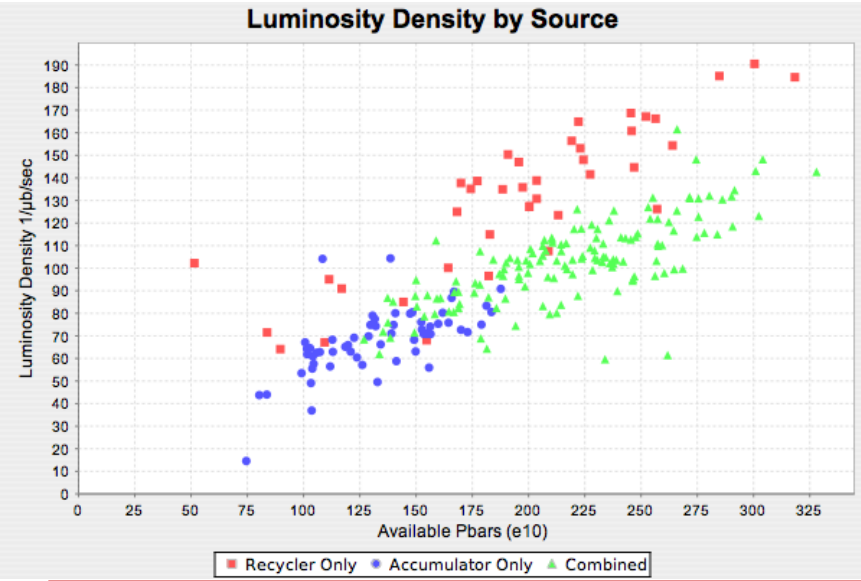
- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005 two months ahead of schedule.
  - By the end of August 2005, electron cooling was being used on every Tevatron shot
- Electron cooling goals
  - Can presently support final design goal of rapid transfers (30eV-Sec/2hrs)
  - Can presently reliably support stacks of 250×10^{10} (FY06 design goal)
  - Have achieved 500 mA of electron beam which is the final design goal.





Recycler-Only Operations

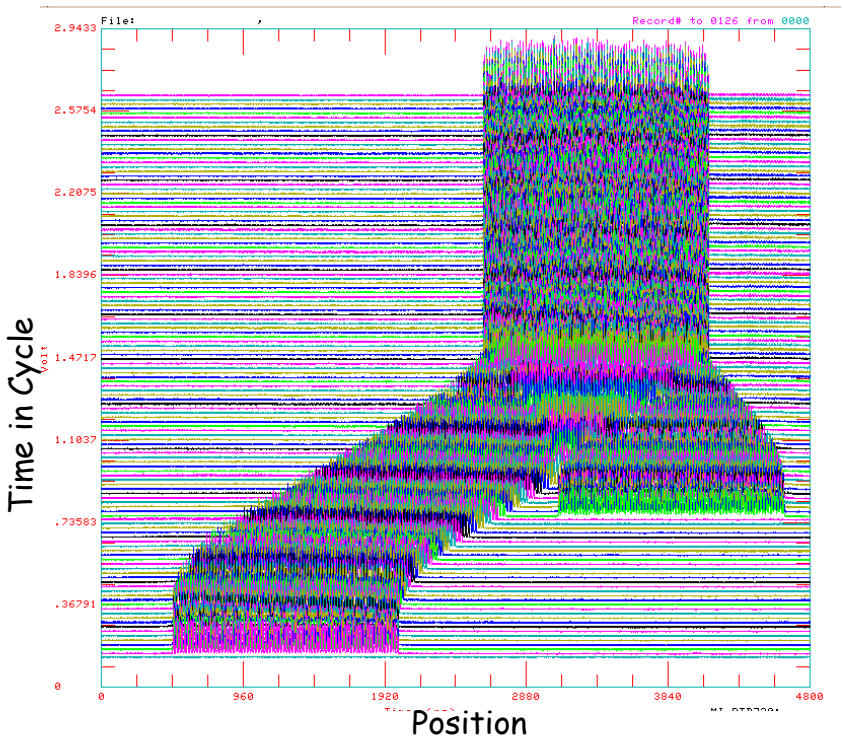
- Recycler had been participating in Collider Operations in the Combined Shot mode because the Recycler Stack size has been limited to ~120x10^{10} pbars
  - Longitudinal Cooling
  - Transverse Stability
- With Electron Cooling operational and the transverse dampers commissioned, the Recycler stack size can now be increased to over 300x10^{10} pbars

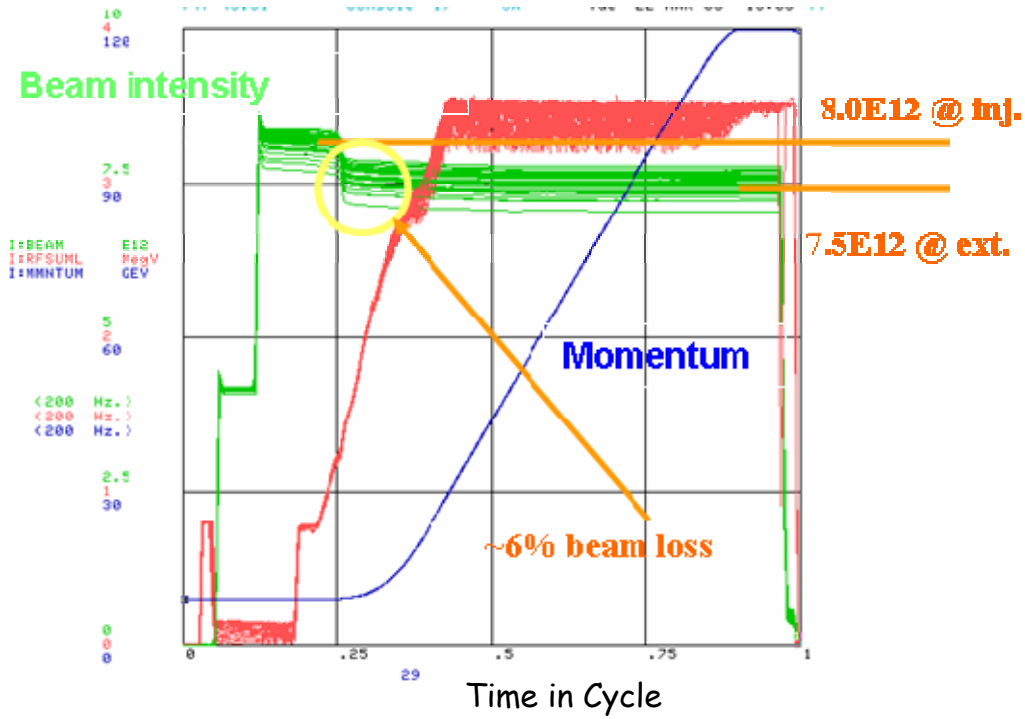


- The Collider complex has transitioned from Combined Shot mode to Recycler-Only mode
  - Faster average stacking.
  - Smaller pbar emittances in the TEV
  - In Recycler-Only mode we no longer need
    - The Accumulator shot lattice
    - Pbar-Tev shot setup
    - Dual energy ramps in the Main Injector
    - Complicated RF states
  - In addition, the Neutrino program benefits because the Accumulator will spend most of the time with small stacks, hence fast cycle times.
- Transition was completed by October 1, 2005 – 1 month ahead of schedule

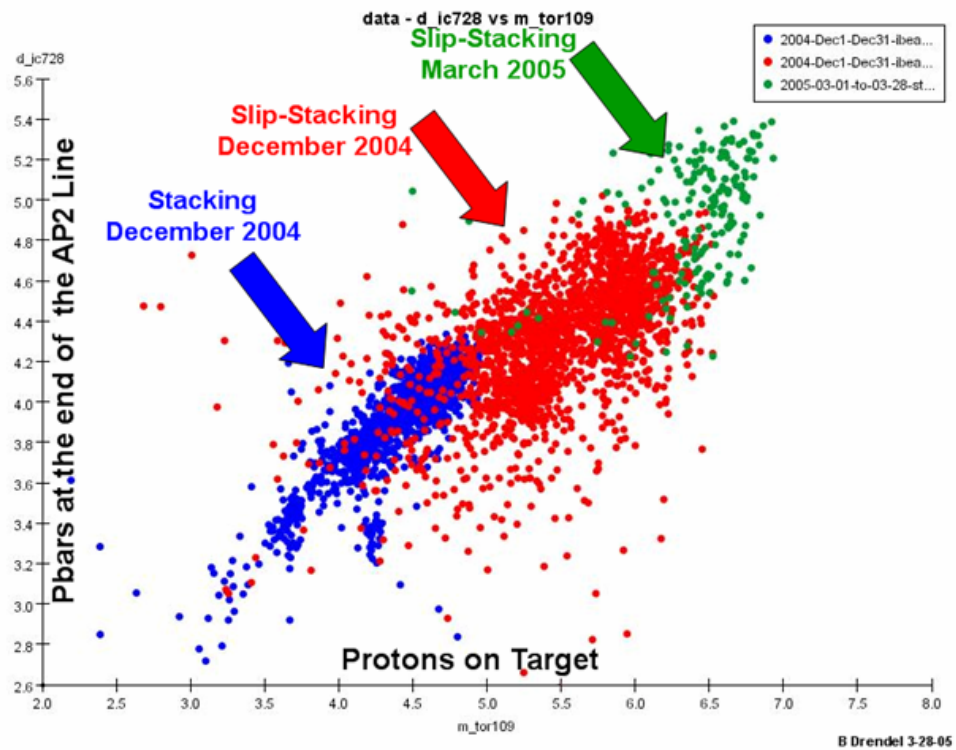
Antiproton Production – Slip Stacking

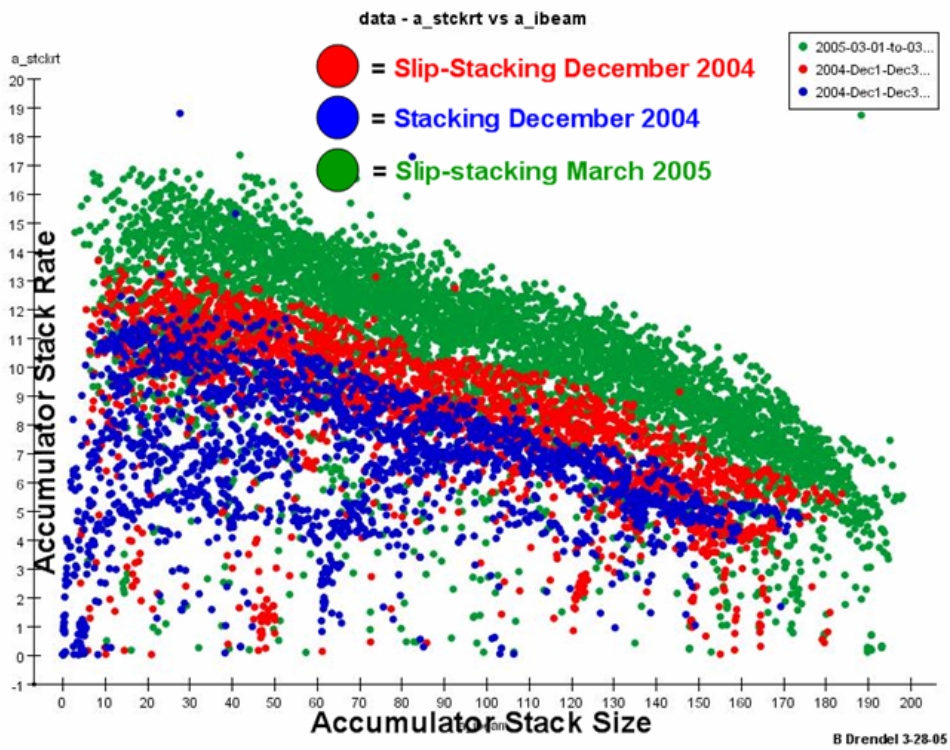
- Slip Stacking is the process of combining two Booster batches at injection into in the Main Injector to effectively double the amount of protons on the antiproton production target





Antiproton Production – Slip Stacking





Protons on Target

- Protons on target has made good progress
- We have been able to sustain:
  - 7.5 - 8x10^{12} protons on target
    - Reached a record 8.5x10^{12} protons on target
    - 90% Slip stacking efficiency
      - Much smaller longitudinal emittance from the Booster
    - Smaller spot size on target
      - Corrected 120 GeV optics
      - Smaller longitudinal and transverse emittances
  - Fast repetition rates (starting at 2.2 seconds)
    - Switch over to Recycler-only operations complete
      - 90% of the Tevatron shots are Recycler-only

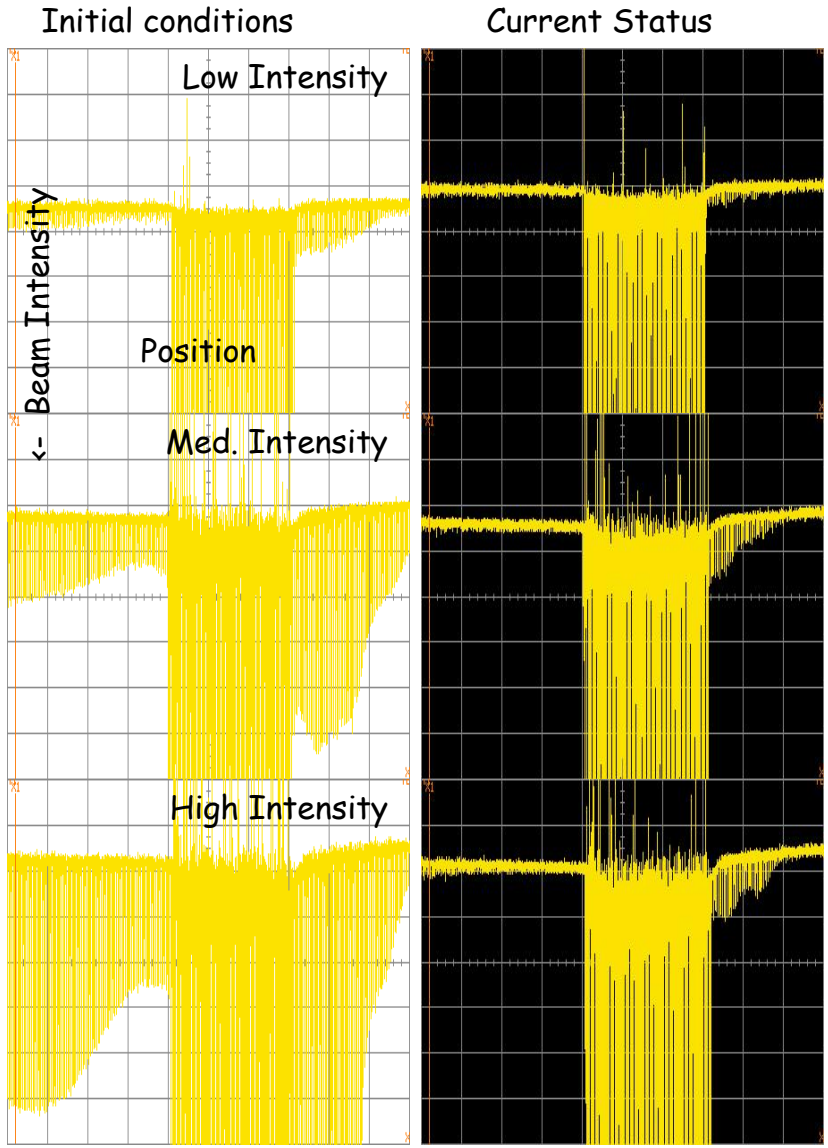
Main Injector Slip Stacking

Goals

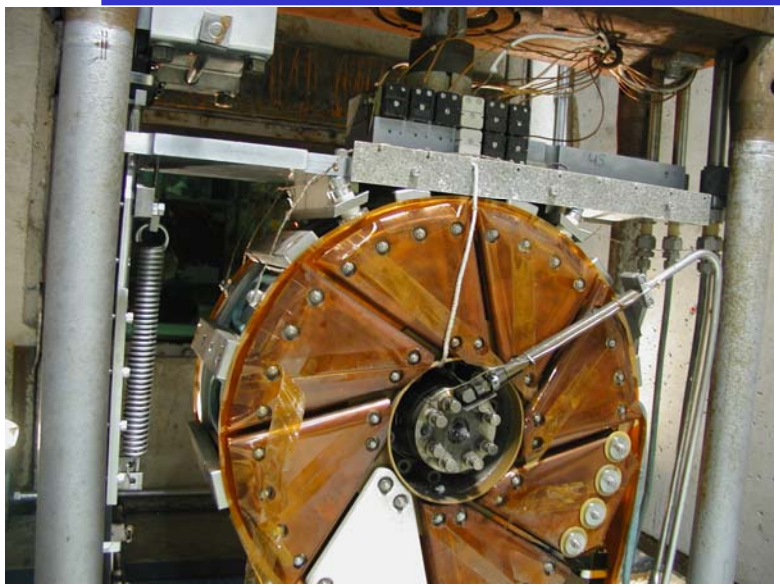
	Initial	3/1/2006	Final	Status	
Intensity	6.2	7.2	8	7.4	$x10^{12}$
Bunch Length	2	1.5	1.5	1.8*	nS
Efficiency	75	95	95	90	%

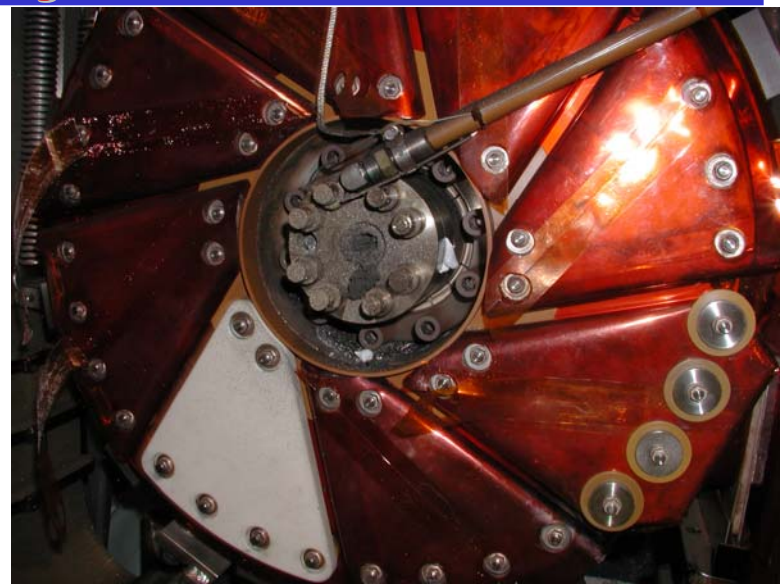
*Effective Bunch length on Mixed Mode Cycles

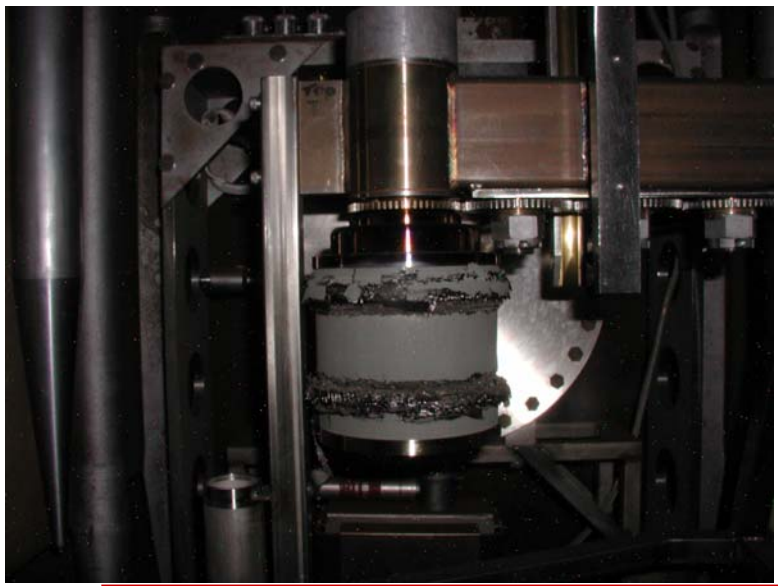
- Remaining Tasks
  - Booster
    - Stronger Mode 1 and 3 damping
    - Transverse Damper
    - 8 GeV Bunch Rotation Reliability
    - RF Step at Transition
    - Operational Streamlining
      - Instrumentation
      - App. Programs
  - Main Injector
    - Reduce effective bunch length on target
      - Beam loading during Mixed-Mode 120 GeV Bunch Rotation
      - Elimination of difference between Pbar-Production-Only cycle and Mixed-Mode cycle
    - Operational Streamlining



An Example of Beam Power: The Antiproton Target Station



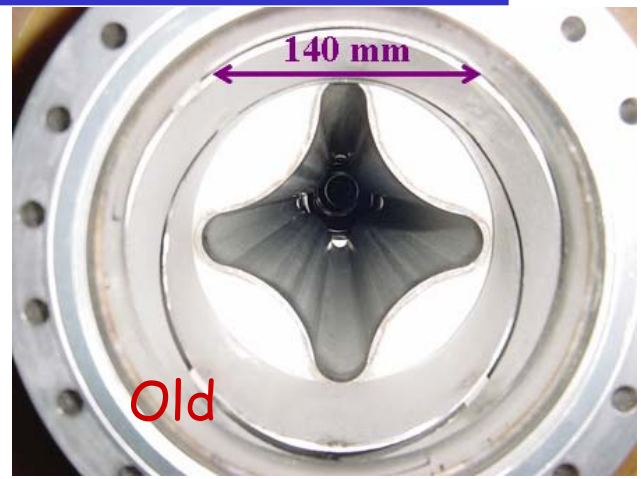




- Total beam power has become a major issue for the first time in the history of the target station.
- Beam power has had a detrimental effect on the target, lithium lens and pulsed magnet.

Antiproton Aperture - Pbar Production

- The measured aperture of the initial stages of the antiproton production chain is about 65% of the available physical aperture.
- An aggressive beam-based alignment program is under development to bring the measured aperture to the physical aperture.
  - Would increase the stacking rate by over a factor of 2
  - The final design goal is to achieve 77% of the physical aperture which will increase in stacking rate by 40%
- The beam based alignment scheme consists of 5 major components
  - Independent control of the quad gradients (done)
  - Beam position measurement system to measure orbit distortion due to varying quad gradients (in- progress)
  - Orbit control devices to center the beam through the quads (done)
  - Moveable control of tight apertures (stochastic cooling arrays) (in progress)
  - Loss monitor system to measure losses at tight apertures (done)
- Most of the recent focus has been to complete the instrumentation upgrade
  - Extremely small beam currents ~10μAmps
- The goal for this year is to increase the aperture for each plane from 65% to 72% of the available physical aperture which would result in a 20% increase in antiproton production rate



Antiproton Aperture - Pbar Production

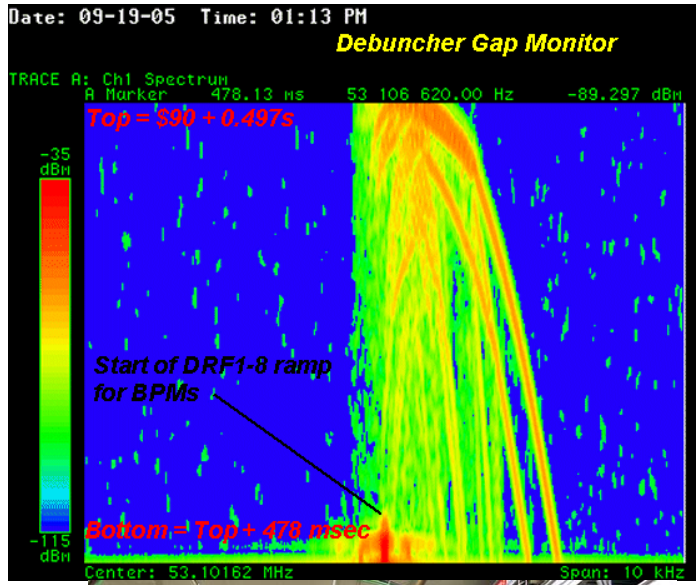
- Aperture increase of AP2 line and the Debuncher is the key component of the Run 2 Upgrades
- The beam based alignment of the AP2 and the Debuncher is not converging (rapidly)
  - Most of the work has to be done with reverse protons
  - Partial alignment is not compatible with operations
- Proposal – Set aside a period of 2 weeks in December 2005 to completely focus on the beam based alignment studies in AP2 and the Debuncher
  - Scheduled Start Date: Monday, December 5, 2005
    - Started November 22, 2005 because of a Tevatron component failure
  - End Date: Monday, December 19, 2005
    - Expected to end studies December 11, 2005

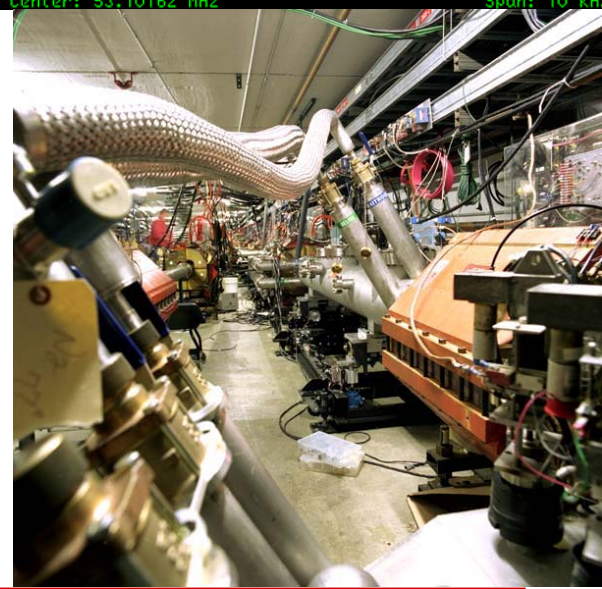
Beam Based Alignment

- For maximum aperture, we would like the beam to go through the center of the quadrupoles
- You cannot trust the absolute position of beam position monitors.
- If the beam goes off center through a quadrupole, it gets a kick. The kick is proportional to
  - strength of the quad
  - the offset of the transverse beam position with respect to the center of the quad.
- To measure how far off center the beam is in the quad
  - Measure the beam trajectory downstream of the quad with BPMs
  - Change the Quad current (strength)
  - Measure the difference in beam position
    - If the beam goes though the center of the quad, the trajectories will be the same
  - Change the position of the beam through the quad with an upstream trim magnet until the quad does not steer the beam.

Beam Based Alignment

- Necessary components
  - Beam position system
  - Individual control of quad strength
  - Trim magnets to control the orbit
- Problems in the Debuncher
  - Beam position system
    - Pbar current extremely low
    - Secondary spray
    - Reverse proton beam loading
  - Quad strength
    - Quads are on busses – had to add lots of shunts
  - Trim magnets
    - There is no space in the Debuncher to add trim magnets
    - Orbit correction is done by placing quads on remote control stands
  - Overall
    - Align with reverse protons
      - Large setup overhead
    - Stack with forward pars
    - Just isn't the same!





Debuncher Study Period Summary

- The Debuncher orbit is vertically aligned
  - Over 1000 orbits recorded
- The Debuncher vertical aperture has been optimized
  - Three rounds of moveable device optimization (70 motors per round)
  - Circulating beam aperture has increased from 230->290π-mm-mrad
- Have measured a 30% distortion in the AP2 lattice.
  - New optics have undergone first round of testing
  - Optics to be implemented by end of study period
- Quad Center alignment of AP2 underway
  - Have removed over 30mm of orbit distortion
- Need finish alignment of the Debuncher Injection septum
  - Will require 6 shifts
- Will need another study period
  - But before, will conduct a mini-review to assess software, hardware, and procedures used in the December study period
  - Optimization of the Debuncher Horizontal Plane
  - Beam-based alignment of the Debuncher to Accumulator Transfer line
  - Quad center alignment of the Accumulator injection orbit

Run II Upgrade Summary

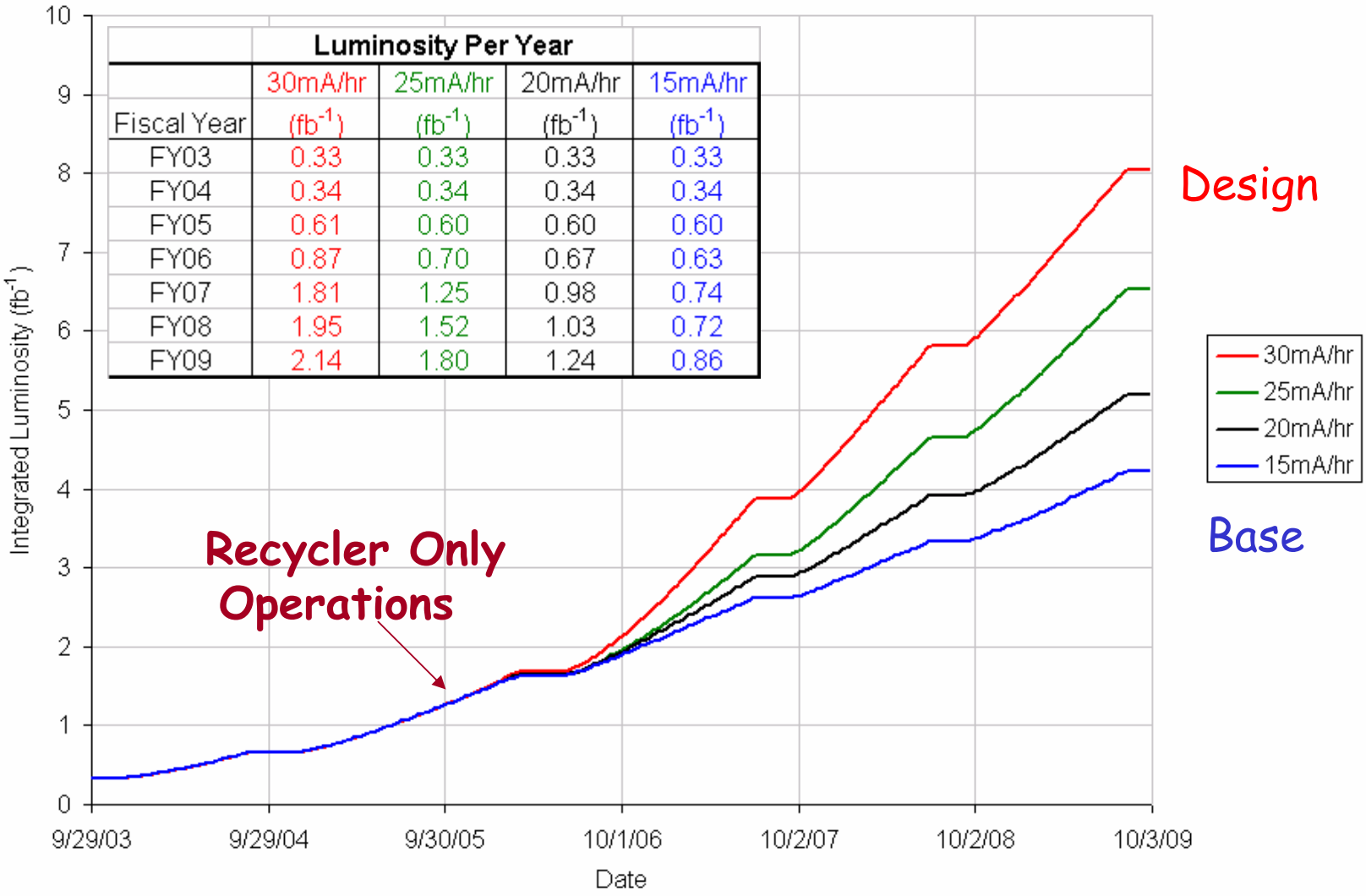
- Recycler is operational
- Electron cooling is operational
- Slip Stacking is operational
- A special team of twenty people is focused on increasing antiproton stacking rate
  - The major focus is optimizing the aperture of the Debuncher and AP2 transfer line which is relatively straightforward accelerator physics

Luminosity Projections

- Our plan is to deliver the design projection,
  - but, develop an understanding of fallback scenarios
  - With electron cooling commissioning going well, the major uncertainty is the stacking rate
- Luminosity Scenarios
  - Design Projection:
    - Electron cooling
    - 15 minute Accumulator to Recycler transfers
    - Peak Stack rates of 30 mA/hr
  - Fall-back Projection:
    - Electron cooling
    - ½ hour Accumulator to Recycler transfers
    - Peak Stack rates of 20-25 mA/hr
  - Base Projection:
    - Electron cooling
    - 3/4 hour Accumulator to Recycler transfers
    - Peak Stack rates of 15 mA/hr

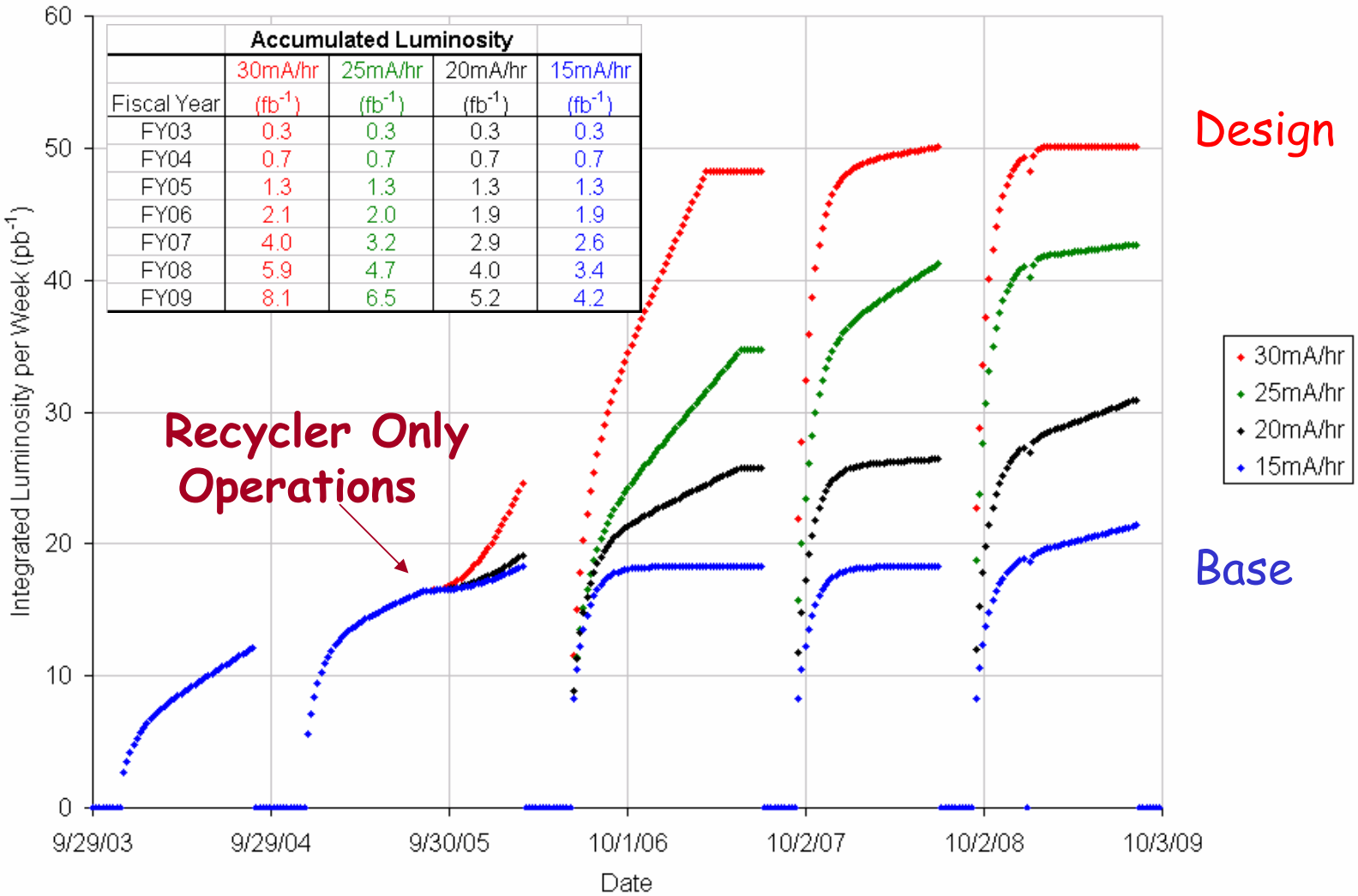
Integrated Luminosity

Luminosity Per Year				
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.33	0.33	0.33	0.33
FY04	0.34	0.34	0.34	0.34
FY05	0.61	0.60	0.60	0.60
FY06	0.87	0.70	0.67	0.63
FY07	1.81	1.25	0.98	0.74
FY08	1.95	1.52	1.03	0.72
FY09	2.14	1.80	1.24	0.86

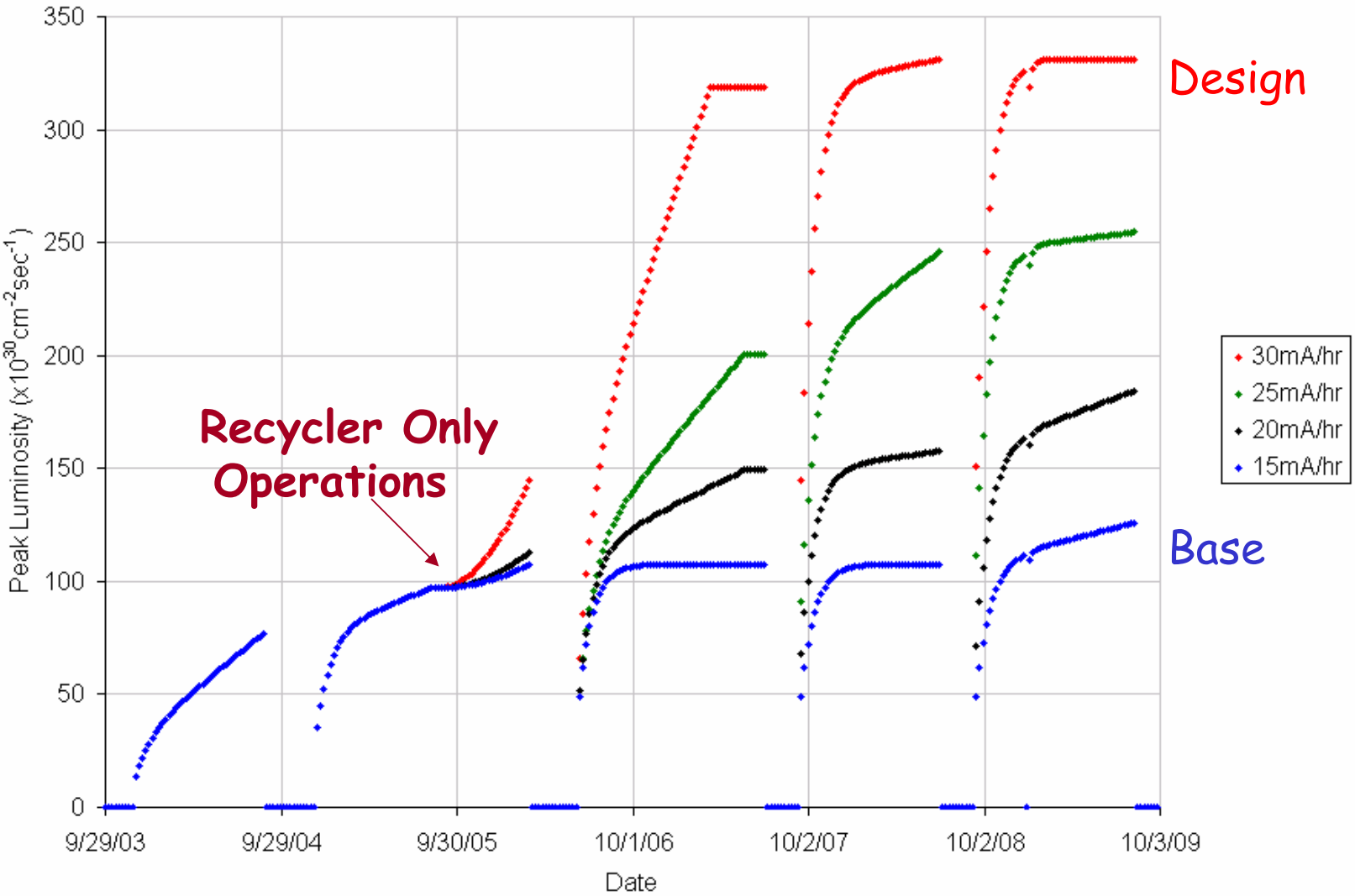


Weekly Luminosity Projection

	Accumulated Luminosity			
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.3	0.3	0.3	0.3
FY04	0.7	0.7	0.7	0.7
FY05	1.3	1.3	1.3	1.3
FY06	2.1	2.0	1.9	1.9
FY07	4.0	3.2	2.9	2.6
FY08	5.9	4.7	4.0	3.4
FY09	8.1	6.5	5.2	4.2

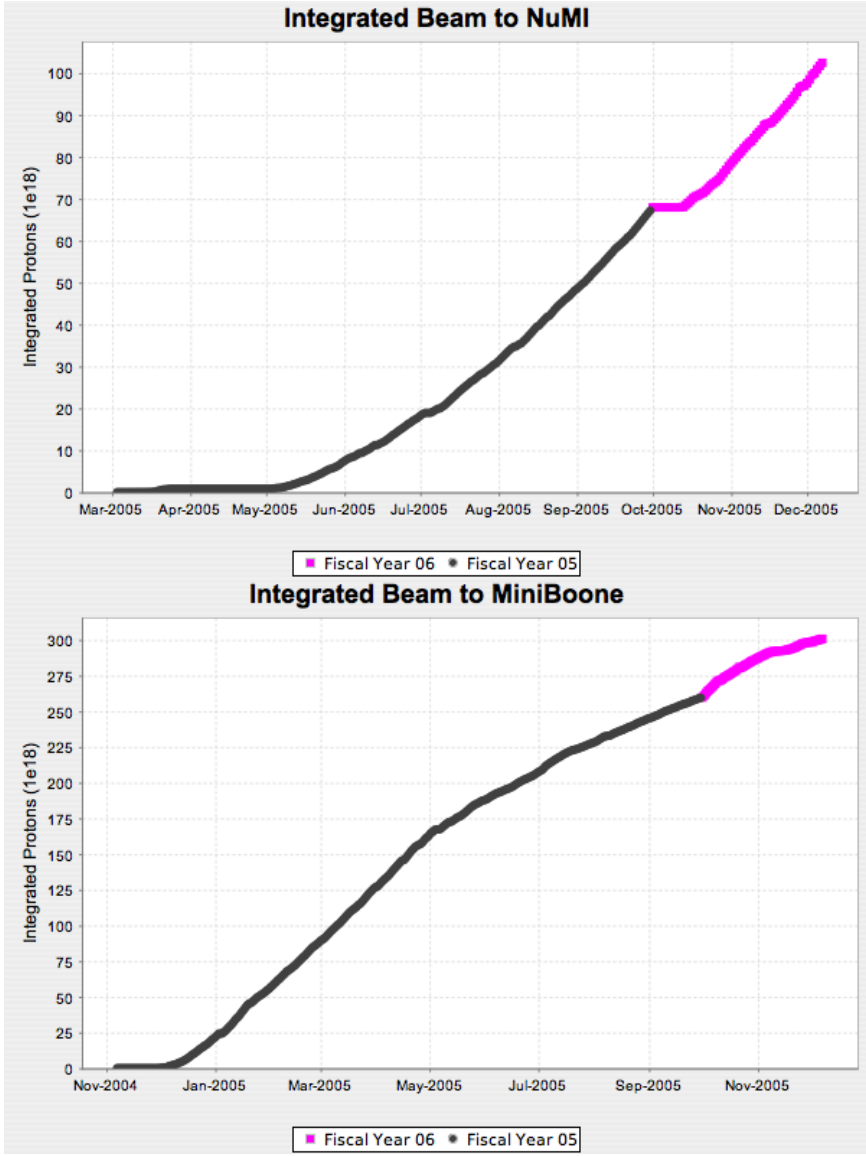


Peak Luminosity Projection



Major Expansion of the Neutrino Program

- NUMI commissioned
  - First beam on Dec. 4, 2004
  - Around the clock operations on March 14, 2005
  - Operations in Mixed-Mode antiproton stacking cycles
  - Target problems April 2005
  - Horn Problems September 2005
  - Running on average at 175-200kW of beam power
  - Reached $1x10^{20}$ protons in December 2005
  - Major issues:
    - Targeting component reliability and availability – Engineering!
    - Pulses per second – tied to pbar stacking
- Record throughput for MiniBoone
  - $8.0x10^{16}$protons/hour
  - Delivered a over $6x10^{20}$protons in three years of running
- Routine running of SY120
  - Developed mixed mode which achieved a factor of 7 more spill seconds then originally allocated
  - Now with NUMI absorbing all the mixed mode cycles, a long flattop ramp keeps most of the spill-seconds intact.



Summary

- The Run II Upgrades are on track to provide over 8fb^{-1} by the end of 2009
  - The Recycler is operational
  - Electron cooling is commissioned and operational!
  - Slip Stacking is operational
- The major challenge left in Run II is the increasing the antiproton production rate
  - AP2- Debuncher aperture upgrade
  - Debuncher to accumulator transfers
  - Rapid transfers between the Accumulator and Recycler